Beyond the standard model with B physics

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Abstract

Extensions of the Standard Model may have significant effects on B physics observables. Two examples of methods that may find such effects are reviewed: Resolving discrete ambiguities in CP asymmetries and detecting right handed currents in radiative B decays.

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1 Introduction

The ultimate goal of the B physics program is to find inconsistencies within the Standard Model (SM) [1], in particular, to find indications for new physics in the flavor and CP violation sectors. Therefore, we should maximize our ability to detect such effects, should they occur. It is the purpose of this talk to describe some ideas in this direction. These ideas emerge from a model independent approach, namely, to look for inconsistencies within the SM in as many ways as possible. In general, new physics can modify the SM effective operators and create new ones that are absent in the SM. In particular, it can add new CP violating phases and significantly modify the flavor changing neutral current operators.

Some of the SM predictions, however, cannot be significantly modified by new physics. It is likely that new short distance physics does not significantly change the SM prediction that decay amplitudes that involve the spectator quark, for example, $B_d \to D_s K$, are small. It is also unlikely for new physics to significantly modify amplitudes that are large in the SM. For example, CKM unsuppressed tree level decays, e.g. $b \to c\bar{u}d$, are likely to be dominated by the SM amplitude. Generically, we expect new amplitudes to be significant only when they compete with loop or highly CKM suppressed SM amplitudes.

Thus, in order for an observable to provide a useful probe of new physics the following three conditions have to be satisfied:

- it should be practically measurable;
- it should have small SM uncertainties;
- it is likely to be sensitive to new physics.

Clearly, an impractical to measure observable is not a good candidate for new physics searches. Similarly, an observable that within the uncertainties of the SM can assume any value, is not sensitive to new physics effects. For example, the measurement of $\sin 2\alpha$, which is very important within the SM framework, is not very sensitive to new physics due to the large uncertainties in its value within the SM. Finally, we like to look for observables where new physics effects are likely to occurs. Ideally, we like to test all the SM predictions. In practice, however, we cannot do it, and in many cases we have to assume the SM. For example, it is very unlikely that new physics

will change the SM prediction that the CP asymmetries in $B \to \psi K_S$ and $B \to \psi K_L$ are opposite in sign. Therefore, the two data samples are combined to enlarge the statistics.

In this talk we give two examples, resolving discrete ambiguities and searching right handed currents in $B \to s\gamma$ decays, that roughly satisfy the above conditions and thus can be used to search for new physics.

2 Resolving discrete ambiguities

If we assume CKM unitarity there are two independent angles in the "unitarity triangle", both of which are related to the underlying non-zero phases of CKM matrix elements. We take them to be α and β and we use the definition $\gamma = \pi - \beta - \alpha$. In B factory experiments we seek to measure quantities that, in the absence of physics from beyond the SM, are simply related to these angles. Ignoring for the moment the effects of subleading amplitudes, time dependence CP violating asymmetries are proportional to $\sin 2\phi$ where ϕ is one of the angles of the unitarity triangle. In particular, the first two CP asymmetries to be measured are likely to be in $B \to \psi K_S$ which measures $\sin 2\beta$, and in $B \to \pi^+\pi^-$ which measures $\sin 2\alpha$.

However, a measurement of $\sin 2\phi$ can only determine the angle ϕ up to a four fold ambiguity: $\{\phi, \pi/2 - \phi, \pi + \phi, 3\pi/2 - \phi\}$ with the angles defined by convention to lie between 0 and 2π. Thus, with two independent angles, there can be a priori a total 16 fold ambiguity in their values as determined from CP asymmetry measurements. These ambiguities can limit our ability to test the consistency between the measured value of these angles and the range allowed by other measurements interpreted in terms of the SM. Within the SM, the present data on the CKM matrix imply that 2β is in the first quadrant ($0 < \beta < \pi/4$), that $0 < \alpha < \pi$, and that there is a correlation between the values of α and β [2]. Thus, among the 16 possible solutions at most two, and probably only one, will be found to be consistent with SM results. Namely, the SM can predict the values of β and almost always of α once $\sin 2\beta$ and $\sin 2\alpha$ are measured.

In the presence of physics beyond the SM the values of the "would be" α and β extracted from asymmetry measurements may not fall within their SM allowed range. Such new physics cannot be detected if the values of the asymmetry angles happen to be related via the ambiguities to values that do

overlap the SM range. Clearly, the fewer ambiguous pairings that remain, the better our chance of recognizing new physics should it occur.

In order to resolve these ambiguities in addition to the values of $\sin 2\phi$, only the signs of $\cos 2\phi$ and $\sin\phi$ for both $\phi = \alpha$ and $\phi = \beta$ need to be determined. These four signs resolve the ambiguities completely: sign($\cos 2\phi$) is used to resolve the $\phi \to \pi/2 - \phi$ ambiguity and sign($\sin\phi$) is used to resolve the $\phi \to \pi + \phi$ ambiguity. Several measurements which can determine sign($\cos 2\phi$) have been proposed [3]. Uncertainties in calculation of hadronic effects do not affect the interpretations of these measurements, although they do depend on the known value of hadronic quantities such as the width and the mass of the ρ. The determination of sign($\sin\phi$), however, cannot be achieved without some theoretical input on hadronic physics. Quantities that are independent of hadronic effects always appear as the ratio of a product of CKM matrix elements to the complex conjugate of the same product. Such pure phases are thus always twice the difference of phases of the CKM elements. Any observable that directly involves a weak phase difference of two CKM elements, ϕ, (rather than 2ϕ) also involves hadronic quantities such as the ratio of magnitudes of matrix elements and the difference of their strong phases. Thus, in order to determine the sign of $\sin\alpha$ or $\sin\beta$ some knowledge about hadronic physics is required.

Below we give two examples of ideas that can be used to resolve discrete ambiguities.

2.1 Cascade mixing and the sign of $\cos 2\beta$

In the first example we explain how to determine sign($\cos 2\beta$) based on cascade mixing [4, 5]. The standard CP asymmetry in $B \to \psi K_S$ is sensitive to $\sin 2\beta$. The reason is that the asymmetry is generated by an interference between the $B_H \to \psi K_S$ and $B_L \to \psi K_S$ decay amplitudes. [B_H (B_L) is the heavy (light) mass eigenstate.] One of the amplitudes is proportional to $\sin\beta$ and the other to $\cos\beta$. The interference is proportional to their product, namely to $\sin 2\beta$. Sensitivity to $\cos 2\beta$ arise when two amplitudes that are proportional to $\sin\beta$ (or $\cos\beta$) interfere. [Recall $\cos^2\beta = 1 - \sin^2\beta = (1+\cos 2\beta)/2$.] The idea of [5] is to use interferences between the $B \to \psi K_L$ and $B \to \psi K_S$ decay amplitudes. Then, there are a total of four amplitudes, two that are proportional to $\sin\beta$ and two that are proportional to $\cos\beta$. When all the four amplitude interfere, there are terms

that are proportional to $\cos^2\beta$ and $\sin^2\beta$.

The problem is that we cannot use the full $B \to \psi K$ sample. We cannot use events where the kaon decay into a final state that identifies its mass. For example, we identify a kaon that decays at time $t_K \gg 1/\Gamma_S$ as a K_L. [Γ_S is the K_S width.] For such decays there are no $K_L - K_S$ interferences. The effects of $K_L - K_S$ interferences can be seen only in events where the kaon decays into a final state that is common to both K_L and K_S. The best candidates are semileptonic decays. As long as $t_K \lesssim 1/\Gamma_S$ there is significant interference between the K_L and the K_S components. The time dependence of the decay chain is given by [5]

$$\Gamma(B(\bar{B}) \to \psi(\pi^-\ell^+\nu)) \propto e^{-\Gamma_B t_B}\Big\{e^{-\Gamma_S t_K}\left[1 \mp \sin 2\beta \sin(\Delta m_B t_B)\right] + e^{-\Gamma_L t_K}\left[1 \pm \sin 2\beta \sin(\Delta m_B t_B)\right] \pm 2e^{-\frac{1}{2}(\Gamma_L+\Gamma_S)t_K} \left[\cos(\Delta m_B t_B)\cos(\Delta m_K t_k) + \cos 2\beta \sin(\Delta m_B t_B)\sin(\Delta m_K t_k)\right]\Big\}, \qquad (1)$$

where t_B (t_K) is the time where the B (K) decay and Γ_S (Γ_L) is the K_S (K_L) width. Note the term that is proportional to $\cos 2\beta$. It is this term that enables us to resolve the discrete ambiguity.

2.2 $B \to \psi K_S$ vs $B \to D^+D^-$

In the second example we explain how to determined $\text{sign}(\sin\beta)$ by comparing the CP asymmetries in $B \to \psi K_S$ and $B \to D^+D^-$. We can write any decay amplitude as a sum of two amplitudes [6]: a tree-dominated amplitude A_T, and a penguin-only amplitude, A_P, with a different weak phase. Then, we define $r \equiv A_P/A_T$. In the case of the angle β we have one class of measurements, from $b \to c\bar{c}s$ processes such as $B \to \psi K_S$, that have very small r. For these channels the CP asymmetry measurement determines β up to the usual four-fold ambiguity

$$a_{\psi K_S} = -\sin 2\beta. \qquad (2)$$

The other class of measurements is from $b \to c\bar{c}d$ decays such as $B \to D^+D^-$. In this case we expect r to be significant. To leading order in r we get

$$a_{D^+D^-} = \sin 2\beta - 2r\cos 2\beta \sin\beta \cos\delta. \qquad (3)$$

where δ is the strong phase difference between A_T and A_P. Comparing Eqs. (3) and (2) we find

$$a_{\psi K_S} + a_{D^+D^-} = -2r\cos\delta(\cos 2\beta \sin\beta). \tag{4}$$

It is clear from this expression that we can fix the sign of $\sin\beta$ only if we know the sign of $\cos 2\beta$ and, in addition, the sign of $r\cos\delta$. We assume the first of these can be determined experimentally by one of the methods mentioned before. Currently, there is no reliable way to determine the sign of $r\cos\delta$. In order to proceed, we must assume a model for hadronic calculation. Assuming factorization and that the top penguin is dominant, we get $r < 0$. Within the factorization approximation the relevant strong phases (almost) vanish, so that $\delta \simeq 0$, and hence the sign of $r\cos\delta$ is given by the sign of r. Assuming $r\cos\delta < 0$ as given by the factorization calculation we get

$$\mathrm{sign}(a_{\psi K_S} + a_{D^+D^-}) = \mathrm{sign}(\cos 2\beta \sin\beta). \tag{5}$$

Note, in particular, that the SM predicts $\cos 2\beta \sin\beta > 0$, and therefore also that the asymmetry in D^+D^- is smaller in magnitude than the asymmetry in ψK_S (and opposite in sign).

3 Right handed currents in $b \to s\gamma$ decays

The measurements of both exclusive and inclusive $b \to s\gamma$ decay rates are in good agreement with the SM predictions. This still leaves open the possibility that new physics could be present, but it manifests itself only in the details of the decay process. For example, the SM predicts that the photons emitted in $b \to s\gamma$ decays are predominantly left-handed. This property does not hold true in extensions of the SM such as the left-right symmetric models, and therefore, can be used to signal the presence of new physics. Unfortunately, in $B \to K^*\gamma$ decay all photon polarization information contained in the final hadron is lost. Therefore, other ways have to be used in order to extract this information. Here be summarize four different ways that have been proposed.

Measuring mixing-induced CP asymmetries in the inclusive $b \to s\gamma$ decay was proposed as an indirect method for probing photon polarization effects in [7]. Since both B and $\bar{B}$ must decay to a common final state, the resulting asymmetry measures the interference of right- and left-handed photon amplitudes. As the SM predicts a very small right-handed admixture of photons

in $b \to q\gamma$ decays, a large mixing-induced CP asymmetry is a signal of new physics. In [8] the $\Lambda_b \to \Lambda\gamma$ decay was studied. Since the decaying particle is a fermion, the photon polarization information can be indirectly extracted using the Λ polarization.

Another way of measuring the photon polarization in the exclusive $B \to V\gamma$ decay makes use of the conversion electron pairs formed by the primary photon. Electron–positron pairs from photons that were produced in the inner part of the detector can be traced and their production plane can be reconstructed with high accuracy. The angular distribution in the relative angle of the $K^* \to K\pi$ decay plane and that of the conversion pair can be used to determine the helicity amplitudes in the $B \to V\gamma$ decay [9]. Actually, the photon does not have to be on shell. The photon can be off shell and we can use the corresponding direct decay $B \to Ve^+e^-$ in the region where the dilepton invariant mass is close to the threshold since there photon exchange dominates the decay [10].

4 Conclusions

Many B physics measurements are aimed to study SM parameters. These measurements also be used to look for physics beyond the SM since by over-constraning the unitarity triangle we may be lucky to find indications for new physics. The measurements we mentioned in this talk, as well as many others, belong to a different class. They are aimed to look for new physics effects. They try to confirm SM predictions: that $\cos 2\beta$ is positive, that the photon in $b \to s\gamma$ is left handed, that the semileptonic CP asymmetry in B_s decays is very small, and many other. Since a major goal of the B physics program is to look for new physics it is important to find and carry out this kind of measurements.

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